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TECHNICAL NOTE

MAXIMUM ISOMETRIC MOMENTS GENERATED BY THE WRIST MUSCLES IN FLEXION–EXTENSION AND RADIAL–ULNAR DEVIATION

Scott L. Delp, Anita E. Grierson and Thomas S. Buchanan

Departments of Biomedical Engineering and Physical Medicine & Rehabilitation, Northwestern University; and Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, Illinois, U.S.A.

Abstract—Maximum isometric and passive moments about the wrist were measured for a range of flexion–extension and radial–ulnar deviation angles in 10 healthy adult males. Each subject was seated in a test apparatus with his shoulder abducted 90°, elbow flexed 90°, and body and forearm constrained. Peak flexion moments ranged from 5.2 to 18.7 N m (mean = 12.2, SD = 3.7), while peak extension moments ranged from 3.4 to 9.4 N m (mean = 7.1, SD = 2.1). The average flexion moment peaked at 40° of flexion, whereas the average extension moment was relatively constant from 30° flexion to 70° extension. Peak moments generated by the radial and ulnar deviators ranged from 7.9 to 15.3 N m (mean = 11.0, SD = 2.0) and 5.9 to 11.9 N m (mean = 9.5, SD = 2.2), respectively. Passive moments in flexion–extension were near zero in the central 150° of motion, but increased at the end of the range of motion. The average passive moment was 0.5 N m in 90° flexion and 1.2 N m in 90° extension. Average passive moments about the radial–ulnar deviation axis were near zero with the wrist radially deviated and at neutral, but increased to 0.9 N m in full ulnar deviation. Copyright © 1996 Elsevier Science Ltd.

Keywords: Wrist; Muscle; Strength.

INTRODUCTION

A biomechanical description of the wrist and the surrounding muscles is needed to help design tendon transfer surgeries and analyze neurologic and musculoskeletal disorders, such as carpal tunnel syndrome and osteoarthritis. The development and testing of a biomechanical model that estimates the moment-generating characteristics of the muscles about the wrist requires accurate knowledge of the normal range of moments produced at that joint.

Surprisingly little work has been done to determine the maximum isometric and passive moments about the wrist. In a study of three subjects, Lehman and Calhoun (1990) reported that the maximum isometric flexion and extension moments about the wrist were nearly constant with changes in flexion–extension angle over the central 80° of motion, but decreased sharply at the limits of motion. Ketchum *et al.* (1978) measured maximum isometric extension moments at one wrist position in 15 subjects, providing a measure of wrist extensor strength. We have not identified any publications that characterize the moments generated by the radial and ulnar deviators over the range of joint motion. Passive moments about the flexion–extension axis have been reported to be near zero in the central range of motion, and to increase greatly at the limits of flexion and extension (Lehman and Calhoun, 1990).

The purpose of this study was to determine the magnitude and angular variation of the moments generated by the muscles about the wrist (including the extrinsic muscles of the hand). Maximum isometric and passive moments for the full ranges of wrist flexion, extension, radial deviation, and ulnar deviation were determined experimentally in healthy subjects.

METHODS

Maximum isometric and passive moments generated by 10 healthy males, aged 23–33, were measured at various joint angles in the flexion–extension and radial–ulnar deviation planes. The subjects had no history of wrist trauma or musculoskeletal disease. After giving informed consent, each subject was seated with the shoulder of his dominant arm abducted 90° and his elbow flexed 90°. His torso was constrained by straps placed around the trunk, and his forearm was held by a custom fixation device (Fig. 1). A fiberglass cast approximately 1.5 cm wide was secured on the subject's hand at the distal metacarpals, leaving the fingers and thumb free. The cast was attached to a six-degree-of-freedom load cell, which has a resolution of 0.56 N (Assurance Technologies Inc., Model 150-600). The load cell was mounted in a custom-built apparatus that rotated about a fixed axis. The center of rotation of the load cell apparatus was aligned with the capitate bone, which approximates the center of rotation of wrist flexion–extension and radial–ulnar deviation (Andrews and Youm, 1979; Brumbaugh *et al.*, 1982; Volz, 1976). The distance from the load cell to the approximate center of wrist rotation was measured for each subject; this distance was used to compute the joint moment from the forces and moments measured with the load cell. The mean distance was 7.5 cm.

During the flexion and extension trials, the subject's forearm was held in 90° of supination. Neutral pronation–supination (0°) corresponded to a position such that the volar surface of the hand was parallel to the ground with the shoulder and elbow flexed 90°. Neutral flexion–extension (0°) was determined when the volar surface of the hand was in line with the long axis of the forearm, as shown in Fig. 1. The subject's interphalangeal joints were held in a flexed position by stiff rubber bands to prevent variation of finger position. Specifically, with the fingers flexed, the rubber bands held the first and third phalangeal segments of each of the four fingers together by passing over the flexed dorsal surfaces of the phalanges. The subject was instructed to produce a maximum flexion or extension moment and was given visual

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Address correspondence to: Scott L. Delp, Ph.D., Sensory Motor Performance Program, Rehabilitation Institute of Chicago (Room 1406), 345 East Superior Street, Chicago, IL 60611, U.S.A.

Fig. 1. Experimental setup. The subject's forearm was strapped into a custom fixation device. The hand was cast at the distal metacarpals and rigidly fixed into a load cell. Surface electrodes were placed across the flexor carpi radialis and the extensor carpi radialis longus or brevis.

feedback showing the forces measured by the load cell and a target set slightly above the maximum level that he was expected to attain. (The target force was determined from a preliminary maximal trial in each direction.) Maximum isometric flexion extension moments were recorded every 20° over the central 120° of motion (from 60° flexion to 60° extension) and every 10° over the remaining range of motion. The wrist remained in 0° of radial–ulnar deviation as the flexion extension angle was changed. To minimize the effects of fatigue over the subject population, the order of the joint angles was randomized. Also, comparing the maximum moments with the wrist in neutral flexion–extension position near the beginning and end of the experiment demonstrated that the moment-generating capacity was not decreased by fatigue over the course of the experiment.

During the radial and ulnar deviation trials, the subject's forearm was held in neutral pronation–supination. The fingers were left unconstrained. Maximum isometric moments were measured at the neutral position for radial–ulnar deviation and at the subject's limits of radial and ulnar deviation. The neutral position for radial–ulnar deviation (0°) was determined by aligning the third digit with the long axis of the forearm with the wrist at 0° flexion.

Data collection progressed at a rate determined by the subject; however, there was at least 30 s between trials. EMG and load cell data were recorded for 1 s at 1000 Hz and then reduced by averaging over the 150 ms window corresponding to the greatest force measured by the load cell. Two measurements were made at each joint angle. Of the two measurements, only the one corresponding to the greater force was used for analysis. The moment vs joint angle curves were computed from the load cell measurements and then ensemble averaged to obtain the average flexion and extension moment curve for the population. Similarly, the maximum isometric radial and ulnar deviation moments were averaged for each of the three wrist positions.

Passive moments were measured as the joint was moved from the neutral position to the end of the range of motion while joint angles were measured with a goniometer. In flexion–extension, the passive moments were measured every 20° over the central 80° of motion and then every 10° to the end of the range of motion. In radial–ulnar deviation, the passive moments were measured every 10° for the central 20° of motion and then every 5° to the limit of motion.

Surface electrodes were placed over the flexor carpi radialis and the extensor carpi radialis longus and brevis to ensure that the muscles were not activated during the passive trials and to obtain a rough estimate of activation and co-contraction during the maximum voluntary contractions. Electrode placement followed the method described by Perotto (1994). The rectified and averaged EMG measurements were normalized to the peak activation in a subject's data set. The level of co-contraction was determined using equation (1), and was considered significant at values greater than 20%.

$$\%\ \text{co-contraction} = \frac{\text{EMG(muscle group as antagonist)} - \text{EMG(passive)}}{\text{EMG(muscle group as agonist)} - \text{EMG(passive)}} \times 100. \tag{1}$$

RESULTS

The maximum wrist flexion moment varied substantially with flexion–extension angle (Fig. 2). The average flexion moment was greatest at 40° of flexion (11.1 N m), but decreased to approximately 50% of the peak in full flexion and extension. The magnitude and location of the peak moment differed among the subjects. The individual peak flexion moments ranged from 5.2 to 18.7 N m (mean = 12.2, SD = 3.7) and occurred between 0 and 70° of flexion. In contrast to the flexion moment, the average extension moment was relatively constant from 30° flexion to 70° extension. The maximum extension moment decreased to 70% of the peak extension moment in full flexion and 30% of peak in full extension. Variability in the strength of the subjects was also apparent in extension; individual peak moments ranged from 3.4 to 9.4 N m.

The average maximum radial and ulnar deviation moments at the neutral position were at least two standard deviations greater than the average moments at the limits of motion. The average radial deviation moment was approximately 35% lower at the limit of motion than with the wrist in the neutral position (Table 1). The average ulnar deviation moment in the fully radially deviated position was 33% less than the moment in the neutral position. In full ulnar deviation, the ulnar deviation moment was 70% less than the moment at the neutral position.

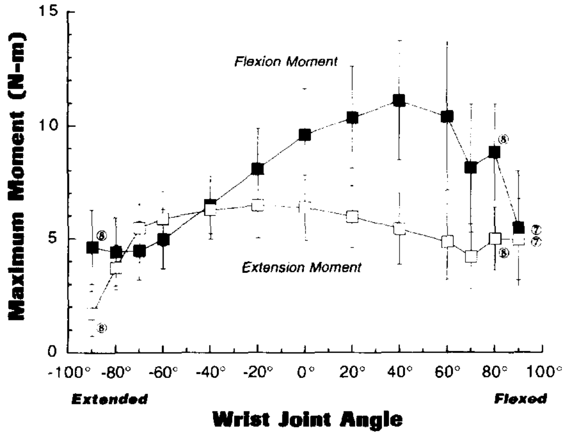

Fig. 2. Average maximum isometric flexion and extension moments vs flexion–extension angle. Each point represents the average of 10 subjects, except where the circled numbers (⑦ ⑧) indicate a smaller number of subjects. The filled squares represent the flexion moments and the open squares represent the extension moments. The error bars indicate the 95% confidence interval. Flexion angles are positive, extension angles are negative. The averaged flexion moments show greater variation with joint position than do the extension moments.

Table 1. Maximum isometric moments generated by the radial and ulnar deviators at full radial deviation, neutral, and full ulnar deviation

	Radial deviators average (range) (N m)	Ulnar deviators average (range) (N m)
Full radial deviation*	7.6 (4.4–10.4)	6.1 (2.0–11.9)
Neutral position	11.0 (7.9–15.3)	9.1 (5.9–11.9)
Full ulnar deviation†	6.9 (1.4–12.4)	2.8 (2.3–7.3)

Measurements were made with the wrist in the neutral flexion–extension position.

*Over the subject population, full radial deviation ranged from 20 to 40° (average = 29°).

†Over the subject population, full ulnar deviation ranged from 30 to 40° (average = 35°).

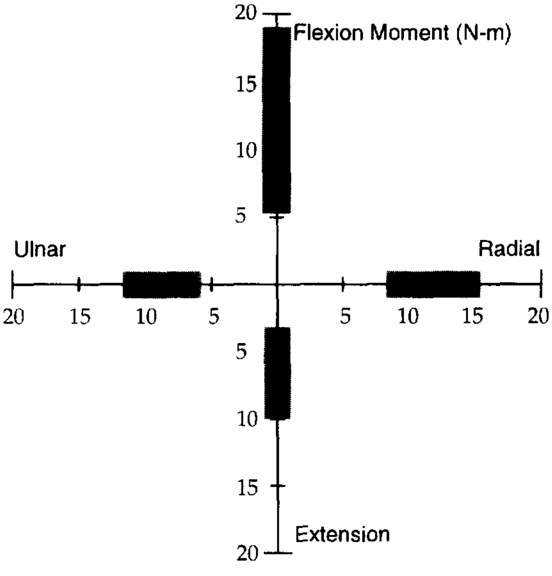

Fig. 3. Comparison of the peak isometric moments (in N m) generated by the flexors, extensors radial deviators, and ulnar deviators. The point represents the average and the shaded areas represent the range.

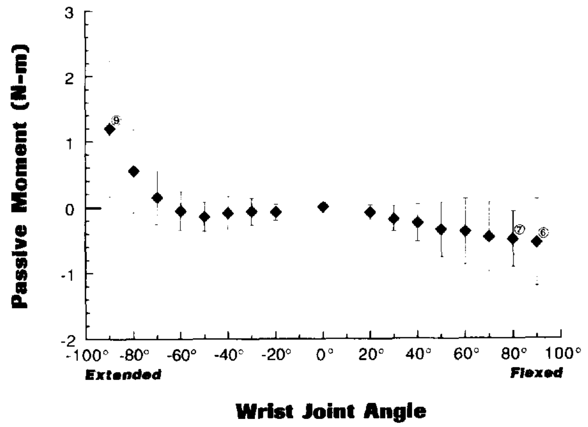

Fig. 4. Passive flexion–extension moments vs flexion–extension angle. Flexion angles and moments are positive; extension angles and moments are negative. Each point represents the average of 10 subjects, except where the circled numbers (⑥ ⑦ ⑨) indicate a smaller number of subjects. The error bars represent the 95% confidence interval. Four subjects with stiff wrists could not attain 90° of flexion, causing underestimation of the average moment at that joint angle.

A comparison of the muscle groups demonstrated that the flexors produced the largest moment, followed by the radial deviators, ulnar deviators, and extensors (Fig. 3). The average peak extension moment was 60% of the average peak flexion moment. Peak extension moments generated by individual subjects ranged from 38 to 75% of their peak flexion moment. The average peak ulnar deviation moment was approximately 80% of the average peak radial deviation moment. Individual peak ulnar deviation moments ranged from 57 to 107% of the subject's peak radial deviation moment; two of the 10 subjects demonstrated greater strength in ulnar deviation than in radial deviation.

Passive flexion–extension moments were not significantly different from zero in the central 150° of motion. The average passive moment increased to 0.5 N m in full flexion and 1.2 N m in full extension (Fig. 4). Four of the 10 subjects could not attain 90° of flexion because of discomfort. Because these subjects had the greatest passive resistance to motion, we believe that the average passive moment was underestimated at 90° of flexion. The subject with the greatest passive flexion moment could not reach 90° extension. The average passive radial–ulnar deviation moments were not significantly different from zero between the neutral position and full radial deviation. However, the average passive moment increased with greater than 20° of ulnar deviation. The average passive moment in full ulnar deviation was 0.9 N m.

Analysis of the EMG data revealed that the average activation of the agonists was constant over nearly the entire range of motion. This suggests that the variation of the maximum isometric moment with joint position was influenced primarily by alterations in muscle lengths and moment arms over most of the range of motion. However, average activation of the flexors with the wrist in full extension decreased sharply to approximately 40% of the peak activation. Similarly, activation of the extensors with the wrist in full flexion was approximately 40% of the peak activation. This suggests that the flexion–extension moments were affected by alterations in agonist activation when the muscles were in the wrist positions corresponding to maximum muscle lengths.

During maximum voluntary contractions of the flexors there was EMG evidence of co-contraction of the extensors in seven of the 10 subjects. That is, co-contraction was greater than 20% [see equation (1)] for at least one joint position during maximum voluntary contraction of the flexors. On average, co-contraction during maximum flexion was observed only for joint angles in the midrange—from 40° extension to 20° flexion. The peak of the co-contraction was 25%, and occurred at the neutral wrist position. Only three subjects showed evidence of co-contraction during maximum voluntary wrist extension tasks.

DISCUSSION

Measurements of muscle strength are used frequently to evaluate neuromuscular function. In this study, maximum isometric moments generated by the muscles about the wrist have been measured over a wide range of joint angles in the flexion–extension and radial–ulnar deviation planes. Results of these experiments demonstrate that the moment-generating capacity of the muscles can vary significantly with joint position.

Before comparing our results to previous publications, it is important to consider the limitations of our study. First, the maximum flexion moments and the passive flexion–extension moments may have been underestimated slightly. When producing a maximum flexion, the majority of the subjects co-contracted their extensors in at least one wrist position, perhaps leading to a lower flexion moment than would have been possible without co-contraction. During passive flexion–extension, some subjects shifted slightly within the experimental apparatus near the ends of the range of motion. Although movement of the subjects was carefully monitored and constrained during the experiments, small changes in limb position have a relatively large effect on the measured passive moment because passive resistance rises sharply near the limits of motion. Nonetheless, our results are similar to previously measured passive moments (Lehman and Calhoun, 1990), which were very small in the center of the range of motion and increased to above 0.5 N m at the limits of motion.

The fingers were observed to tense during the maximum contractions. In preliminary trials, subjects were unable to perform maximum wrist contractions while leaving the fingers flail. We therefore instructed subjects to produce maximum wrist moments that included contributions of the digital flexors and extensors. Based on the cross-sectional areas (Lieber *et al.*, 1990, 1992) and the moment arms (Brand, 1985) of the extrinsic muscles of the hand, we expect that these muscles contributed substantially to moments about the wrist. For wrist flexion, the large digital flexors (flexor digitorum profundus and flexor digitorum superficialis) potentially provide twice the moment-generating capacity of the 'dedicated' wrist flexors (flexor carpi radialis and flexor carpi ulnaris) at the neutral position. For the wrist extension, the dedicated wrist muscles (extensor carpi ulnaris, and extensor carpi radialis longus and brevis) provide roughly 55% of the total moment-generating capacity, whereas the extensor digitorum communis provides roughly 30%. Thus, we expect that our experimental measurements include large contributions from the extrinsic hand muscles in addition to the primary wrist muscles.

If the fingers were left unconstrained during the maximum flexion and extension trials, subjects varied their finger positions as the wrist angle was changed, presumably to place the muscles on a more advantageous segment of the length–tension curve. To provide a more consistent position of the fingers, we constrained the interphalangeal joints with stiff rubber bands. Thus, the flexion and extension moments reported here represent this constrained condition. Very little change in finger positions was observed in radial–ulnar deviation; we therefore left the subjects' fingers unconstrained while measuring radial and ulnar deviation moments.

Differences between the axis of wrist rotation and the axis of our load cell device may introduce errors in the measured wrist moments. The load cell was placed as far as possible from the approximate axis of wrist rotation to minimize the effects of misalignment of the axes of rotation. The mean distance from the axis of wrist rotation to the load cell was 7.5 cm; thus, a 7.5 mm error in the location of the rotation axis would introduce roughly a 10% error in the computed moment.

The maximum isometric radial and ulnar deviation moments were measured at only three locations. Therefore, a full examination of the variation of the radial–ulnar deviation moments with joint angle is not possible based on our data. While further measurements are necessary to determine the angular variation, this study provides the first step towards characterizing the strength of radial and ulnar deviators.

The maximum moments generated by our subjects agree well with previously reported wrist moments. The average extension moment at the neutral wrist position is within one standard deviation of the average maximum extension moment reported by Ketchum *et al.* (1978) in this wrist position. The magnitudes of the maximum isometric flexion and extension moments also agree well with those reported by Lehman and Calhoun (1990). However, our results contradict the finding of Lehman and Calhoun (1990) that the maximum isometric flexion moments are independent of flexion–extension angle for the central range of wrist motion. Maximum wrist flexion moments measured in our study varied substantially with flexion–extension angle. The conflicting conclusions from the two studies may result from differences among subjects. Although all of our subjects showed some variation of maximum flexion moment over the central range of motion, the amount of variation with joint angle differed between subjects. The three subjects examined by Lehman and Calhoun (1990) may not have revealed the variation with joint angle as clearly as the 10 subjects examined here.

The device used in this study could provide a useful clinical tool. Measuring changes in maximum wrist moments in patients with neurological and musculoskeletal disorders could provide important information needed to quantify the severity or progression of the disorder. Accurate assessment of wrist muscle strength could also help document the efficacy of a rehabilitation program.

It was interesting to discover that the maximum isometric flexion moment peaks with the wrist in flexion, where the muscle fibers are relatively short. It is frequently assumed that muscle force-generating capacity increases with muscle length. Based on this assumption one might expect that muscle moment-generating capacity would peak at longer muscle lengths. This is *not* the case for the wrist flexors, and two factors may account for this. First, the moment arms of some of the wrist flexor muscles increase as the wrist is flexed (Brand, 1985). Second, some of the wrist flexor muscles may operate on the descending region of the force–length curve, as demonstrated by Lieber *et al.* (1994) for the extensor carpi radialis brevis muscle. Future work is needed to determine how the muscle moment arms, force–length relations, and activations contribute to the moment-generating characteristics measured in this study.

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